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Electromagnetic Waves with Frequencies Near the local Proton Gyrofrequency: ISEE-3 1 AU observations

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ABSTRACT

Low Frequency (LF) electromagnetic waves with periods near the local proton gyrofrequency have been detected near 1 AU by the magnetometer onboard ISEE-3. Transverse peak-to-peak amplitudes as large as $\Delta\vec{B}/|B| \sim 0.4$ have been noted with compressional components $(\Delta|B|/|B|)$ typically ≤ 0.1. Generally, the waves have even smaller amplitudes. The waves are highly elliptically/linearly polarized and are often, but not always, found to propagate nearly along $\vec{B}_0$. Both right- and left-hand polarizations in the spacecraft-frame have been detected. The waves are detected during all orientations of the interplanetary magnetic field, with the Parker spiral orientation being the most common case. Although there are some differences in these wave properties from those recently detected at (5 AU) by Smith et al. (1993), the similarities lead one to think that both may be due to the. same physical process. For these 1 AU waves two physical processes are possible: solar wind pickup of neutral (interstellar?) particles and generation by relativistic electron beams propagating from the Sun. The weight of the evidence presently leans towards the former hypothesis. Further analyses will be necessary to rule out one or the other.

INTRODUCTION

Interstellar neutrals because of their lack of charge, freely enter our heliosphere. As the neutrals get close to the sun, they become ionized by photoionization and charge exchange (with solar wind protons). The freshly created interstellar ions will constitute a ring-beam in the solar wind frame. The ion velocities in the plasma frame arc substantially greater than the local magnetosonic and Alfvén wave phase speeds, thus the ions arc subject to resonant instabilities leading to the generation of Low Frequency electromagnetic waves (WU and Davidson, 1972; Brinca, 1991; Gary, 1991; Bogdan et al., 1991). Because the interstellar ions initially have very small velocities relative to interplanetary spacecraft, any waves generated will be detected at the local ion cyclotron frequency . This is directly analogous to the cometary case where cometary pickup ion waves are detected at the local ion cyclotron frequency (Tsurutani and Smith, 1986; Tsurutani, 1991). in this paper, this wave signature will again be used as an argument for local ion pickup.

Gloeckler et al. (1993) have recentl y detected interstellar pickup protons for the first time by instrumentation onboard the Ulysses spacecraft. Gloeckler et al. (1993) have identified the pickup particles by their shell-like pitch angle distributions and cutoff velocities equal to twice the solar wind speed. These observations were made at a distance of 5 AU from the Sun, as Ulysses was on its way to and from Jupiter.

Waves generated by interstellar ion pickup have been identified (Smith et al., 1993) at times concurrent with the Gloeckler et al. (1 993) ion detection. The waves are found to have frequencies near the local proton cyclotron frequency, as theoretically expected. I'here is not a one-to-one correspondence between the wave and ion detection, however. The waves are detected only during intervals when the average magnetic field was directed radially toward or away from the Sun, rather than azimuthally oriented. Smith et al. (1993) also performed a search for similar waves near 1 AU using the Pioneer and Ulysses spacecraft data during intervals of radial fields, but did not find such emissions.

The purpose of this paper is to describe, for the first time, the detection of small amplitude waves with periods near the local proton gyrofrequency detected near 1 AU. The International-Sun-Earth-Explorer-3 (ISEE-3) magnetometer (Frandsen et al., 1978) data was used in the survey. The waves have many features which arc similar to those detected at 5 AU, but also some differences as well. An intercomparison between the waves at the two different radial distances will be made.

APPROACH

High time resolution (6 vectors s-]) ISEE-3 magnetic field data (Frandsen et al., 1 978) was used in a survey to search for Low Frequency waves at 1 AU. our initial intent was to search for waves that were associated with energetic solar flare particle events. An interval during the particle event onset and during the peak particle flux was selected for seven flare events occurring during 1978-1981. Thus, fourteen intervals of time, composed of 6-24 hours duration each, were studied. These arc listed in l'able 1. No regard was taken as to the direction of the interplanetary magnetic field. After the. waves were discovered, five more one-hour intervals were analyzed in high time resolution. These intervals were chosen so they were at least 24 hours prior to the solar cosmic ray events to avoid the possibility of energetic particle generation. These intervals arc also listed in the Table.

RESULTS

LF waves were detected in most of the intervals selected, both during the solar cosmic ray events and prior to the events. They arc usually of small amplitude, arc sporadic in occurrence, and therefore may have been missed in previous surveys. An example of waves in one interval is shown in Figure 1. This example was selected because the waves had unusually large amplitudes and thus were particularly easy to identify. These transverse waves have a peak-m-peak transverse amplitude of -7 nT in a - 18 n']' field or $\Delta\vec{B}/|B| \sim 0.3$. The compressional component, $\Delta|\vec{B}|/|B|$, is less than 0.05. The wave period varies from 4 to 6s. The local proton cyclotron period is 3.6s, thus the waves have periods slightly longer than the local T_p. Note. that the interplanetary magnetic field (GSE coordinates) components arc B_x -- 11 n']' anti B_y -11 nT. 'l'his is a positive (outward) Parker spiral field direction. B_z --8 nT.

Figure 2 gives the hodogram for one cycle of the wave packet in Figure 1 in Principal Axis Coordinates. The Principal Axis Analysis (Sonnerup and Cahill, 1967) method identifies the direction of maximum, intermediate and minimum variance, standardly labeled as $\hat{B}_1$, $\hat{B}_2$ and $\hat{B}_3$, respectively. The minimum variance direction is the wave propagation ($\hat{k}$) direction (Smith and Tsurutani, 1976) for electromagnetic waves. The time interval of the field is 0438:08 to 0438:14 UT. The beginning of the interval is indicated by a "1)" and the end of the interval with an "E". The ambient magnetic field is out of the paper. The wave is left-han(i elliptically polarized ($\lambda_1/\lambda_2 = 30.6$), propagating at an angle of 59" relative to the ambient magnetic field.

Figure 3 gives the power spectrum of the waves from 0416-0439 UT day 158, 1979, the same general interval of lime as in Figure 1 and 2. A fic.ld-aligned coordinate system is used, with $\hat{B}_1$, along the average field direction, $\hat{B}_2$ in the $\hat{B}_1 \times \hat{\Omega}_n$ direction (where $\hat{\Omega}_n$ is the direction of the north ecliptic pole), and $\dot{B}_3$ completing the right-hand system. The power spectra for |B| and the two transverse components, B_2 and B_3, arc plotted. A broad increase in wave power can be noted near f - 2 $\times 10^{-1}$ Hz, the local proton cyclotron frequency (denoted by f_p). The power is - 3-5 nT^2 Hz^{-1} in the transverse components and 5 x 10-1 nT^2 Hz^{-1} in the compressional component. The wave compressional component is about an order of magnitude lower than the transverse components.

Figure 4 is an example of the waves detected wc1l prior to the solar cosmic ray event. The event is from 0033-0035 UT May 8, 1981, while the particle onset is at - 1800 UT May 9, 1991. The six cycles of a wave between 0033:30 and 0034:20 UT have a period of - 8.5s,. The waves arc a mixture of right- and left-hand polarization and propagate at angles between 3° and 19° relative to the ambient magnetic field. The wave is highly elliptically polarized in each cycle $(\lambda_1/\lambda_2$ ranges bet ween 3.3 and 40.5). The local ion proton cyclotron frequency is ~ 9.9s, so these waves have frequencies slightly higher than the local $\hat{\Omega}_p$.

“J’able 2 gives the results of Principal Axis Analysis of a number of wave cycles from Figures 1 and 2 and three other intervals as well. From the ‘J’able, we find that the wave periods arc close to proton cyclotron period, they arc often, but not always, found to propagate nearly along $\vec{B}_o$, and they arc typically highly elliptically to linearly polarized. A mixture of right-hand and left-hand polarizations have been detected. When a sense of rotation can be found, the typical sense is left-handed in the spacecraft frame.

Sixteen short 4-minute intervals where waves were present were selected at random. Figure 5 displays the GSE-B_x and -B_y components of the average field for these intervals. Most of the intervals lic along the Parker spiral dire.ction (this is the most probable direction of the field, so there is nothing unusual about this orientation). ‘J’here is no tendency of the field to be in the radial direction.

DISCUSSION

The waves discussed in this paper have many properties that arc similar to those detected by Ulysses at 5 AU: the waves have small amplitudes relative to the ambient magnetic field magnitude (the Ulysses waves arc slightly larger) and have frequencies near the local proton cyclotron frequency. Both the 1 and S AU waves are a mixture of left-hand and right-band polarization, with left-hand waves more prominent. The waves discussed in this paper are elliptically to linearly polarized. The general polarization of the 5 AU waves was not reported (Smith et al., 1993), but the one example shown was circularl y polarized propagating along the magnetic field ($\theta_{kB} = 5$“).

The one major difference of the waves at 1 AU is that they are detected during all field orientations, with the Parker spiral orientation the most likely. The 5 AU waves are detected when the field is radial. In either case, the pickup ions would generate right-hand waves propagating toward the Sun through the ion resonant beam instability. Because the solar wind speed is larger than the wave phase speed, these waves would be convected in the antisolar direction and would be detected as left-hand polarized (at the proton cyclotron frequency) in the spacecraft frame.

It seems likely that the LF waves reported here are due to hydrogen ion pickup in the solar wind at 1 AU. The persistence of wave detection at frequencies near the local proton gyrofrequency almost rules out other possibilities. Resonant interactions with relativistic - 1 MeV electrons propagating from the Sun is a possible alternative generation mechanism. However, some of the wave events were detected when relativistic electrons were clearly absent. Also, because solar flare electron events typically have broad power-law type velocity distributions and are not monoenergetic in nature, it would be difficult to explain the limited frequency range of the waves. Generation by solar flare protons would generate right-hand polarized waves propagating in the solar wind direction. These waves would be detected as right-hand in the spacecraft frame, at odds with present observations. Although the general ambiguity of the waves and lack of dependence on solar wind stream structure makes this latter possibility less likely, it cannot be ruled out at this time. Clearly further detailed and statistical work needs to be done to clarify our present understanding.

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Table 1. Intervals analyzed for the presence of waves. The top twelve intervals correspond to solar energetic ^{3}He intervals. The bottom five intervals precede the ^{3}He events by at least 24 hours.

Table 2. LF wave properties. The columns correspond to the date, time (UT), wave period, local proton gyroperiod, wave propagation direction relative to the ambient magnetic field, PAA eigenvalue ratios, and sense of polarization.

Figure 1. LF waves with periods near the local proton gyrofrequency.

Figure 2. A hodogram for one wave cycle of the event shown in Figure 1,

Figure 3. Power spectra of the magnetic field for an interval containing the event in Figure 1. The local proton gyrofrequenc y (f_p) is denoted. B_2 and B_3 correspond to power transverse to the average field direction.

Figure 4. Same as Figure 1, but well upstream of a solar energetic ^{3}He event.

Figure 5. The IMF orientation for sixteen wave events selected at random.

TABLE 1

INTERVAL	DATE	DAY	START TIME	STOP TIME	REMARKS
1	SEP 23, 1978	266	0800	1900	Event onset
2	SEP 25, 1978	268	0600	1300	Peak flux
3	JUN 06, 1979	157	1100	1700	Event. onset
4	JUN 07, 1979	158	0000	0600	Peak flux
5	AUG 19, 1979	231	1400	2000	Event onset
6	AUG 20, 1979	232	1200	**1800**	Peak flux
7	SEP 14, 1979	257	0800	**0200** (258)	Event onset
8	SEP 17, 1979	260	1100	1900	Peak flux
9	APR 24, 1981	114	1200	1832	Event onset
10	APR 25, 1981	115	1800	2400	Peak flux
11	MAY 10, 1981	130	0000	2400	Onset through peak
12	MAY 16, 1981	136	0500	**0500** (137)	Onset through peak

Intervals Preceding Solar Cosmic Ray Events

INTERVAL	DATE	DAY	START TIME	STOP TIME
1	SEP 22, 1978	265	0000	0100
2	JUN 05, 1979	156	0000	0100
3	AUG 18, 1979	230	0000	0100
4	APR 23, 1981	113	0000	0100
5	MAY 08, 1981	128	0000	0100

ISEE-3 WAVES

DATE	TIME	Tw	T_p	θ_{kB}	λ_1/λ_2	λ_2/λ_3	Pol
9/23/78	1314:16-31	10.0s	12.5s	8°	12.2	4.1	l.h. ellip.
9/23/78	1314:42-46	4.0s	12.5s	24°	7.7	9.1	l.h. ellip.
6/0'7/79	417:30-38	4.5s	4.0s	4°	5.5	6.8	linear
6/07/79	437:47-54	5.0s	3.6s	42"	14.0	5.0	r.h. ellip.
6/07/79	438:08-14	5.0s	3.6s	59"	30.6	1.8	Lh. ellip.
9/14/79	1041:37-50	7.5s	12.3s	68"	70.2	1.7	linear
9/14/79	1041:49-59	10.0s	12.3s	8°	7.5	43.4	r.h. circ/ellip.
9/14/79	1141:48-54	4.55	12.2s	5"	9.8	1.9	l.h. ellip.
9/14/'79	1141:43-03	6.5s	12.2 s	6"	4.()	7.3	l.h. ellip.

TABLE 2.

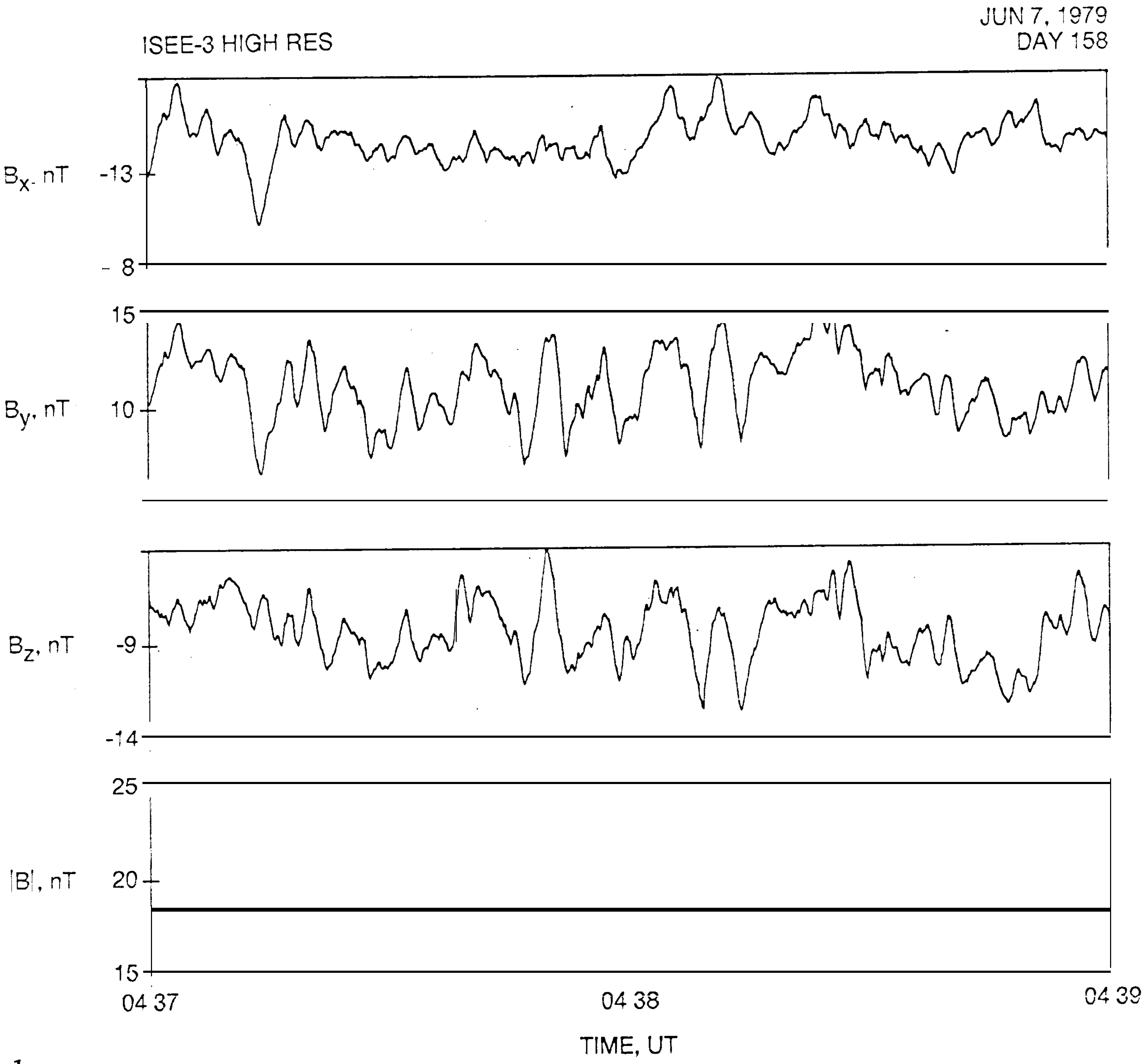

ISEE-3 HIGH RES
JUN 7, 1979
DAY 158
Bx, nT
-13
- 8
By, nT
15
10
Bz, nT
-9
-14
|B|, nT
25
20
15
04 37
04 38
04 39
TIME, UT

Fig. 1

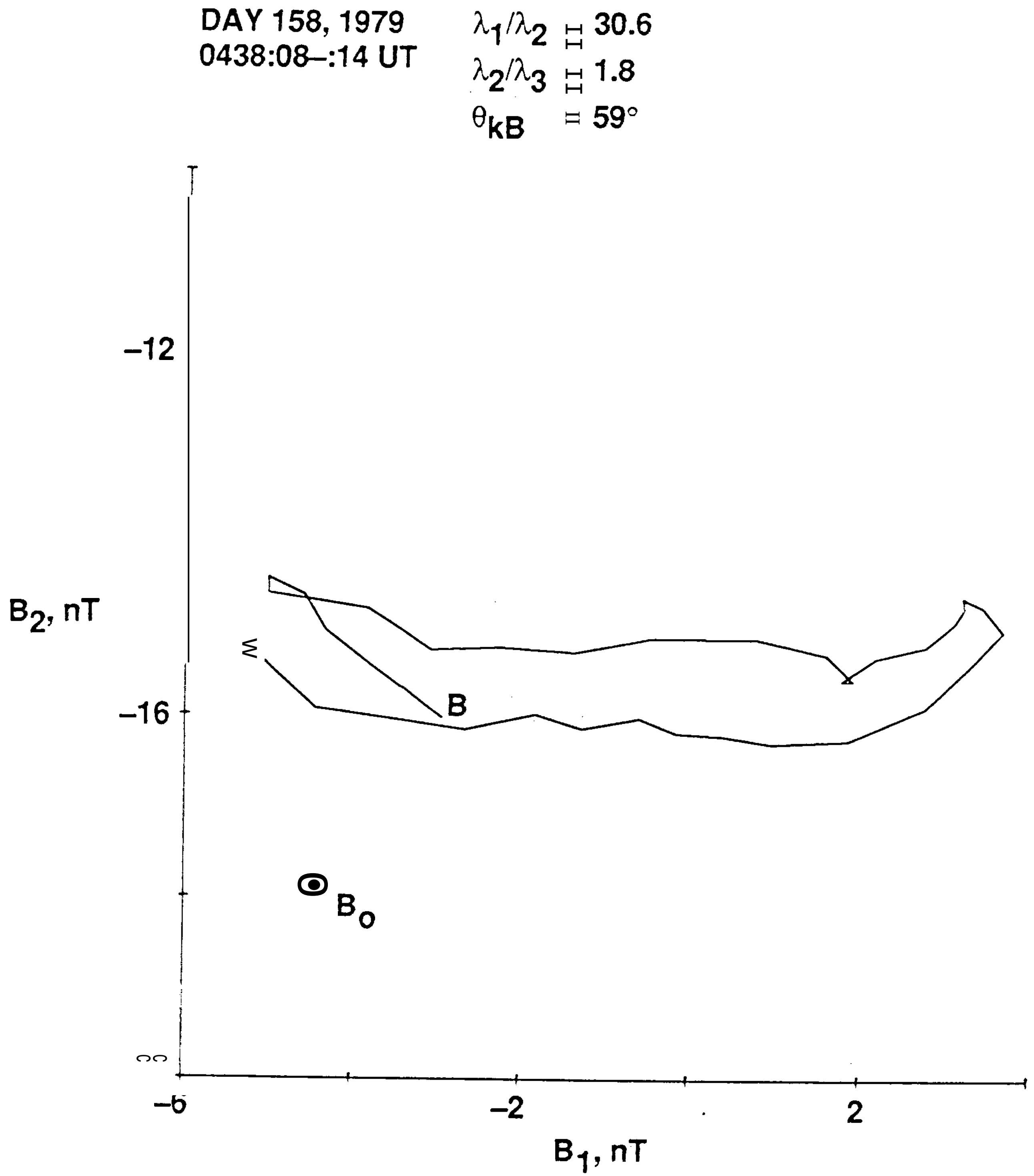
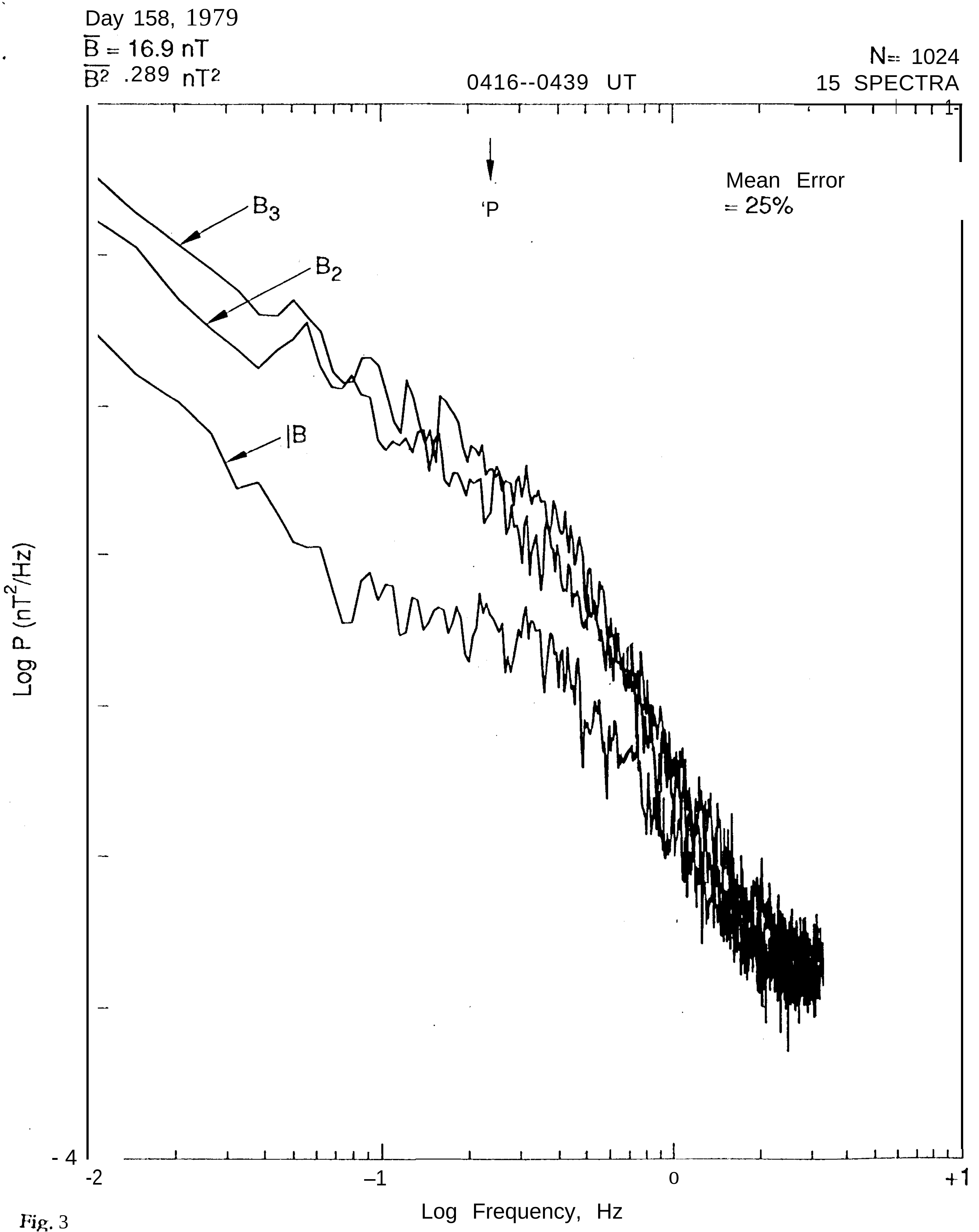
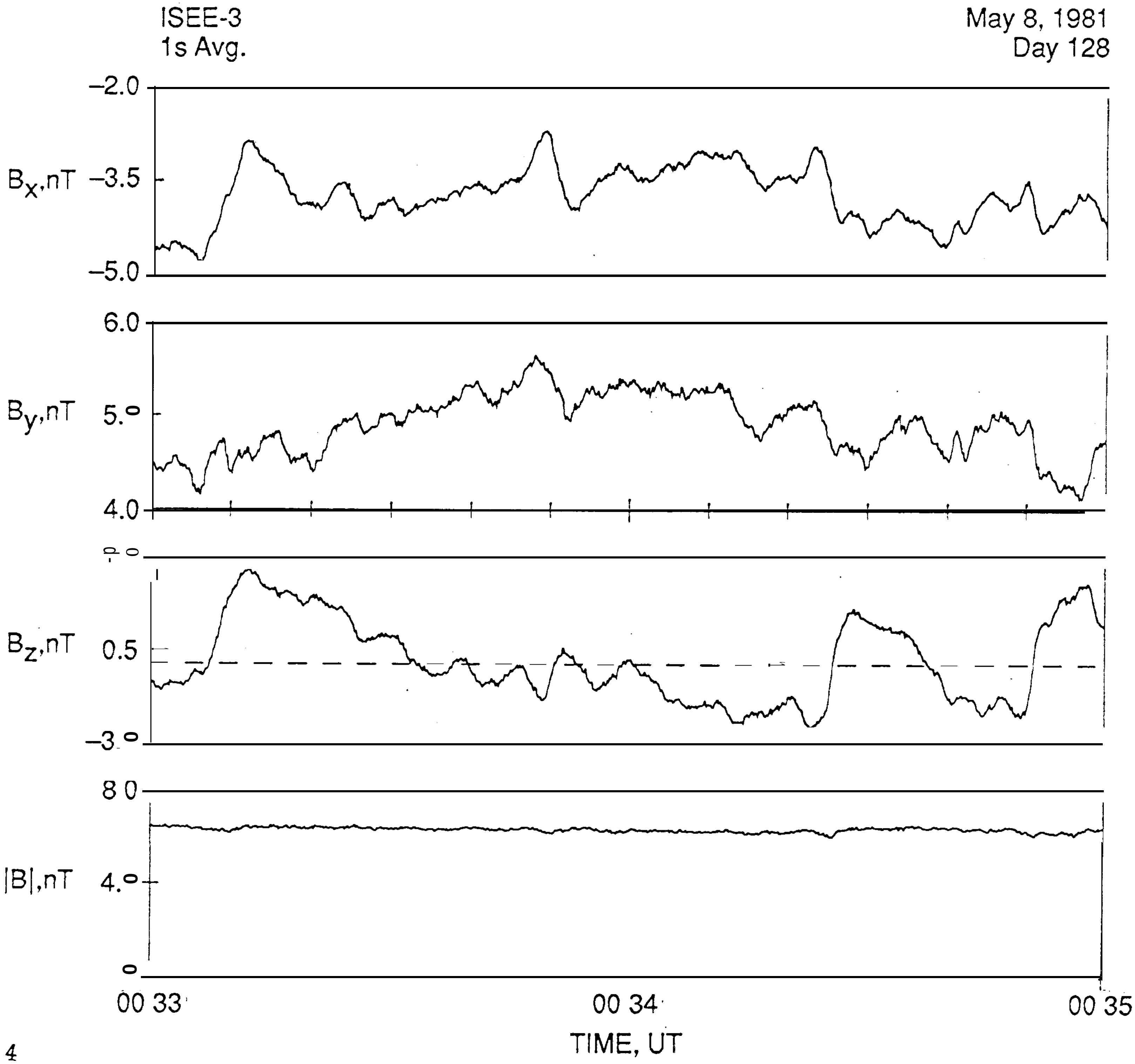

DAY 158, 1979
0438:08–:14 UT
λ_1/λ_2 = 30.6
λ_2/λ_3 = 1.8
θ_{kB} = 59°
–12
–16
B_2, nT
W
B
B_o
–6
–2
2
B_1, nT

Fig. 2



Day 158, 1979
$\overline{B}$ = 16.9 nT
$\overline{B^2}$ .289 nT2
N= 1024
15 SPECTRA
0416--0439 UT
Mean Error
= 25%
P
B3
B2
|B
Log P (nT2/Hz)
-4
-2
-1
0
+1
Log Frequency, Hz

Fig. 3



ISEE-3
1s Avg.
May 8, 1981
Day 128
B_x,nT
B_y,nT
B_z,nT
|B|,nT
−2.0
−3.5
−5.0
6.0
5.0
4.0
0.5
−3.0
8.0
4.0
0
00 33
00 34
00 35
TIME, UT

Fig. 4

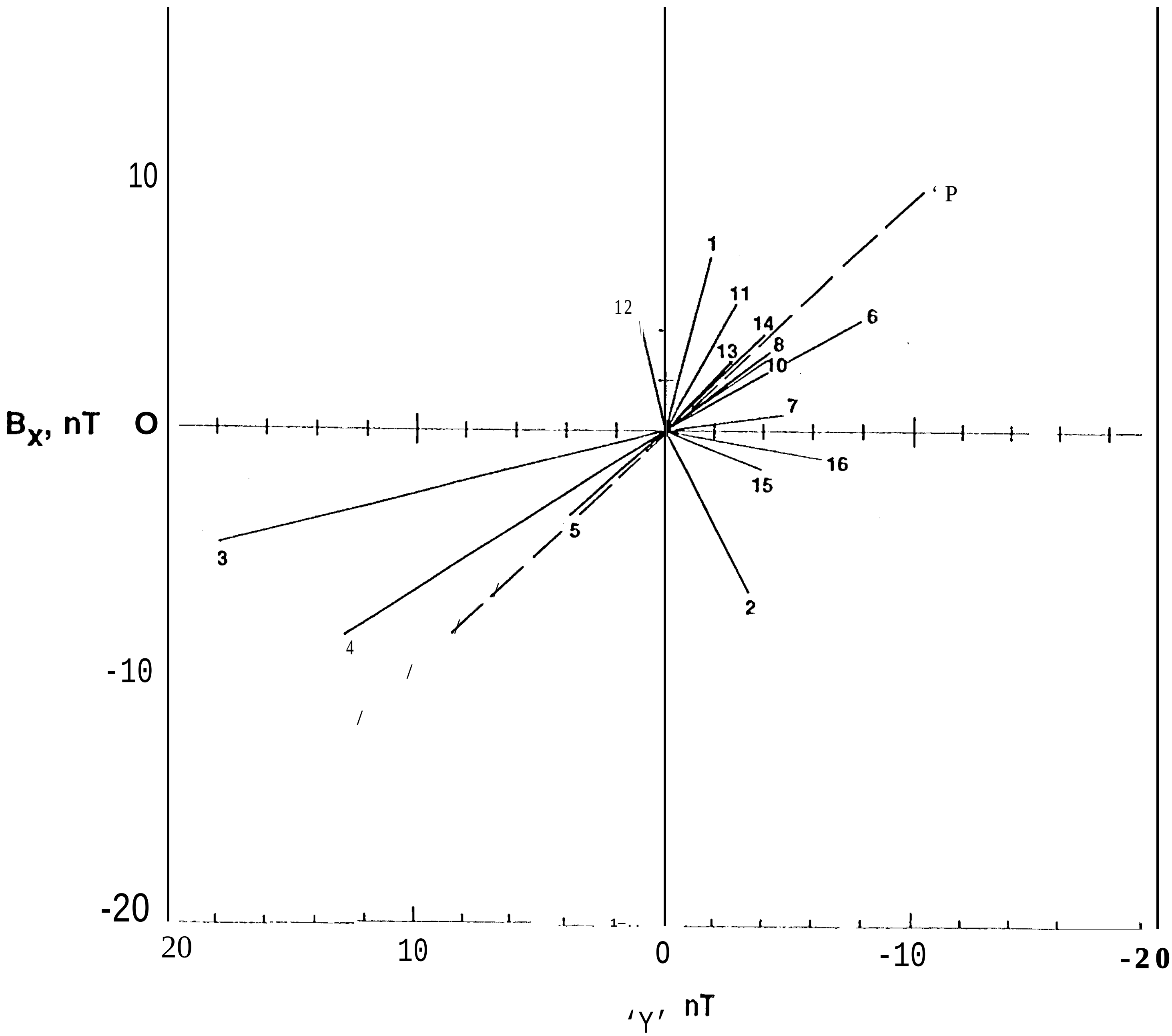


Fig. 5